HYBRID Q-SWITCH DEVICES, LASERS USING THE SAME, AND METHOD OF OPERATION

Cross Reference to Related Application

[0001] This application claims the benefit of U.S. Provisional Patent Application Serial No. 60/443,424 filed January 29, 2003.

BACKGROUND OF THE INVENTION

Field of the Invention

[0002] The present invention relates generally to laser devices, and more particularly, Q-switches and methods of Q-switching for pumped laser systems.

Discussion of the Prior Art

[0003] Many laser applications, such as remote sensing, radar, and laser-induced breakdown spectroscopy (LIBS), demand high peak laser power. In general, for a certain pulse energy, the shorter the duration of the pulse, the higher the peak power. Although ultra-short (<100ps, $1ps=10^{-12}s$) laser pulses can be generated through complicated mode-lock method, the energy per pulse is normally very low due to intrinsically high pulse repetition rate (>MHz). For high energy and peak power pulses, Q-switching is the most-often the choice because its repetition rate could be under several hertz.

[0004] There are many different Q-switch methods and they are generally divided into two categories, i.e., "active" and "passive". Active Q-switch is controllable on

pulse reproduction but bulky and expensive, while passive Q-switch is small and inexpensive, but lack control.

[0005] The most widely used active Q-switches are electro-optic (EO) and acoustic-optic (AO) Q-switches. They require complicated electronic control circuits and bulky EO or AO crystals (e.g., about 20~30mm in length). The advantages of an active Q-switch are the free control of pulse repetition rate and the high pulse reproducibility (low time jitter and high pulse-to-pulse stability). The pulse duration is largely dependent on the rise-time of the electronic control signal and the corresponding response of the EO or AO crystal. EO Q-switches are able to generate sub-10ns (nanosecond= 10^{-9} s) pulses while AO Q-switch normally delivers sub-100ns pulses.

[0006] Rotating a cavity mirror or a chopper is also an active way to Q-switch a laser. It is relatively simple and has been utilized in early embodiments of laser devices. The advantage of this method is simplicity and lossless when the Q-switch is totally opened or aligned. However, it has been revealed that a laser Q-switched with only a rotating element is not able to produce short-duration high-peak-power pulse due to slow evolution from edge cut to entire open. As the laser pulse is actually formed before the entire open, it suffers high loss. Use of a rotating element is now virtually obsolete due to the difficulty of obtaining short-duration and high-peak pulse with this method.

[0007] Passive Q-switches only need a saturable absorber that is placed inside the laser cavity. The absorber prevents the laser from lasing by greatly absorbing energy at the lasing wavelength until it is saturated. Once saturated, the absorber suddenly becomes transparent to the lasing wavelength so that the energy stored in the laser medium is triggered to release in a short period to form a short laser pulse. The absorber will then recover to its initial state and

be ready for the next cycle. A microchip Nd:YAG laser with Cr^{4+}:YAG absorber has been demonstrated to generate pulses shorter than 300ps as described in United States Patent No. 5,394,413.

[0008] Passive Q-switches are simple and are able to generate sub-ns or even shorter pulses. However, the timing of the onset of the absorber becoming transparent fluctuates upon inevitable variations of pumping power, pumping wavelength, temperature, and other cavity related parameters. The pulse repetition rate changes along with pumping power and is also dependent on various parameters of laser medium, absorber, and cavity geometry. Therefore, a laser with a passive Q-switch lacks pulse generation control in terms of repetition rate and pulse-to-pulse time jitter and energy stability. Furthermore, under continuous-wave pumping, the repetition rate of a passive Q-switch laser is typically too high for getting highest peak power. Additionally, a laser with a passive Q-switch must operate near the threshold in order to prevent the occurrence of sub-pulses, which greatly limits the laser output.

[0009] The disadvantages of a passive Q-switch could be largely eliminated by an active Q-switch, and vise versa. Thus, to some degree, active and passive Q-switches may be considered characteristically complimentary.

[0010] It would thus be highly desirable to provide a laser device that implements both active and passive Q-switching in a manner so as to obtain the benefits of both embodiments while minimizing the disadvantages of each.

[0011] It would further be highly desirable to provide an innovative hybrid Q-switch that combines both active and passive system physically and characteristically for laser devices requiring high-peak pulse power.

Summary of the Invention

[0012] According to one aspect of the present invention, there is provided a hybrid Q-switch device for a microchip laser device. The hybrid Q-switch comprises active and passive means of loss modulation, whereby Q-switch cycles from closing (maximum loss) to opening (minimum loss). Active Q-switches may be of the type that do not have moving parts and employ means such as an electric field or an acoustic wave to actively modulate the cavity loss. The passive means of loss modulation is implemented by a saturable absorber that absorbs light (high loss) until becoming saturated (low loss). The active and passive means are, respectively, an active element, such as state-of-art EO and AO Q-switches, or a rotating chopper, etc., and a solid state saturable absorber, such as Cr^{4+}:YAG.

[0013] Another aspect of the present invention is to provide a microchip laser for generating repetition-rate-controllable pulse with pulse widths ranging from about 50.0ps to 10.0ns. According to this aspect of the present invention, the microchip laser comprises two mirrors forming a resonant cavity, a solid-state laser medium, such as Nd:YAG, Yb:YAG, and Nd:YVO_4, and a chopper/absorber hybrid Q-switch.

[0014] Advantageously, the hybrid Q-switch laser of the invention emits pulses, which are well regulated and of high energy per pulse as from a conventional active Q-switch laser and have short duration as from a conventional passive Q-switch laser. Due to shorter pulse duration and combined cavity loss modulation, as will be explained hereinafter, the hybrid Q-switch laser consumes less power and implements simpler electronics to generate pulses of certain peak power than a corresponding active Q-switch laser.

Brief Description of the Drawings

[0015] The objects, features and advantages of the present invention will become apparent to one skilled in the art, in view of the following detailed description taken in combination with the attached drawings, in which:

[0016] Figure 1 depicts a conventional laser with an active Q-switch;

[0017] Fig. 2 depicts a conventional laser with a passive Q-switch (saturable absorber);

[0018] Fig. 3 depicts a laser device with a hybrid Q-switch according to the present invention; and,

[0019] Fig. 4(a) depicts a microchip laser device with a chopper/absorber hybrid Q-switch according to the present invention and Fig. 4(b) depicts a rotary chopper blade having a number of openings (slits).

Detailed Description of the Preferred Embodiments

[0020] Fig. 1 shows a typical active Q-switch laser comprising a laser medium 13 for providing optical gain, and an active Q-switch 14 and two mirrors 11 and 12 at the ends of an enclosed cavity to enhance stimulated emission. Although not shown in Figure 1, the laser medium is end-pumped with an energy pump source 10 which may comprise a semiconductor laser, a solid-state laser, or a gas laser. If pumped with flash lamp, then the laser cavity and the laser medium would normally be designed for side pumping.

[0021] The active Q-switch 14 could be an acoustic-optic (AO) Q-switch that utilizes a bulk AO crystal, such as quartz and $TeO2$, and it requires a high-power radio frequency source to generate acoustic wave propagating through

the crystal to diffract out lasing wavelength. Lasers with AO Q-switch can emit sub-50ns pulses. For sub-10ns pulses, electro-optic (EO) Q-switch would be more often being employed. In an EO Q-switch, an EO crystal, such as KDP, BBO, and $LiNbO_3$, would be used. The cavity loss modulation is realized by changing the crystal's birefringent characteristic through applying kilovolt electric pulses on the crystal. The crystal could be several centimeters long for lowering high voltage requirement.

[0022] For explanation purpose, it is assumed that an EO Q-switch is adopted in the laser of Fig. 1. The EO Q-switch 14 is driven by high-voltage electric pulse 15 through +/- electrodes. A laser pulse 20 is generated from the laser at the lasing wavelength. The pulse repetition rate can be precisely defined by adjusting the frequency of the electric pulse. The duration of the laser pulse is largely dependent on the rise time (~several ns) of the electric pulse. An EO or AO Q-switch is able to produce stable and well-defined pulses. However, it is bulky and costly and needs complicated electronics, and is not suitable for obtaining pulses shorter than several nano-seconds.

[0023] In the past decade, passive Q-switches have been extensively studied and already applied in the commercial laser products. It uses a saturable absorber, such as Cr^{4+}:YAG, to absorb the intended lasing wavelength to prevent lasing for a period and then the absorber gets saturated and suddenly becomes transparent to enable the lasing. The absorber will recover to the unsaturated state before the laser medium is pumped to an extent sufficient for another lasing.

[0024] Passive Q-switch is simple, compact, and low lost, and does not require electronic power supply. Fig. 2 shows a typical passive Q-switch laser with a saturable

absorber 16. The absorber 16 is a solid-state material that is absorption-saturable to the intended lasing wavelength. It includes Cr^{4+}:YAG, Cr-doped forsterite, Cr-doped gadolinium scandium gallium garnet, saturable semiconductor material, and semiconductor-doped glass, etc. For example, the saturable absorption for Cr^{4+}:YAG is ranging from 900nm to 1200nm.

[0025] Studies have revealed that passive Q-switch could be used to produce pulses in the pico-second (ps) regime. Zayhowski (U.S. Patent No. 5,394,413) has demonstrated a Nd:YAG/Cr^{4+}:YAG microchip laser with <300ps pulse output. A Nd:YVO_4 microchip laser with 56 ps pulse output is reported by Braun et al (Opt. Lett., v22 p381, 1997), where a semiconductor anti-resonant Fabry-Perot saturable absorber is utilized.

[0026] Although a passive Q-switch could generate sub-ns pulse, the energy per pulse is very limited (typically under 10uJ) due to intrinsically high repetition rate and near threshold pumping. Near threshold pumping is required for preventing the occurrence of sub-pulses. Compared to active Q-switch, pulses from passive Q-switch normally have larger time jitter and peak-to-peak power fluctuation, because the timing of the onset of the absorber becoming transparent fluctuates upon the variations of pumping power, pumping wavelength, temperature, and other parameters. This latter problem is addressed by the present invention by coupling the triggering of the passive switch to an active Q-switch.

[0027] That is, according to the present invention, a hybrid Q-switch is provided that comprises means of both active and passive loss modulations. Fig. 3 is a laser embodied with a hybrid Q-switch of the invention comprising an active Q-switch 14 and a saturable absorber element 16 (passive switch). In one embodiment, as shown in Fig. 3, the absorber element 16 is located in the cavity to the emission

(right) side of the active Q-switch 14 as shown in the figure. It may also be positioned at the left side or even bonded together with the active Q-switch crystal.

[0028] The sequence of laser function is as follows: The laser medium 13 is continuously pumped by pumping source 10, e.g., an optical pumping source, such as another laser energy from a laser diode. During this pumping time, the active switch is closed (the passive switch is also in the closed state because there is no light to saturate the absorber) and cavity loss is maximized such that the laser medium absorbs energy thereby effectively increasing the gain of the device to a certain or even gain-saturated level. Then, the active Q-switch 14 is opened (i.e., active Q-switch induced cavity loss is reduced to a minimum) when an electric pulse 15 comes (or, as will be explained hereinbelow, when the slit of a rotary chopper is aligned with the lasing medium). At that time the laser will then commence lasing at noise level at the intended lasing wavelength, which will be partially absorbed by the absorber 16 and will eventually cause the absorber to become saturated (i.e., passive absorber induced cavity loss is reduced to a minimum). As a result, the total cavity loss drops dramatically and the laser starts oscillation above noise level and forms the front part of a pulse. The pulse grows and then drops quickly as it consumes all or most of the gain stored in the laser medium within a short duration. Then the lasing will discontinue and the absorber 16 will recover to its initial state (i.e., the passive switch closes again). Subsequently, the active Q-switch will become closed again to complete a full pulsing cycle. It should be understood that the active switch may be closed before the absorber fully recovers to its initial state. The time window of the active Q-switch being opened equals the duration of the electric pulse 15 and should be

narrow enough to avoid sub-pulsing (i.e., not more than one pulse within one opening window).

[0029] There is a time interval between the opening of the active Q-switch and the onset of saturation of the absorber. The laser will fire a pulse only when or after the absorber is saturated. Therefore, the absorber also acts as a time-delayer of pulsing. Once the active switch is entirely opened, the cavity loss modulation is only depended on the passive absorber and thereby the duration of the laser pulse is determined by the passive absorber and other cavity parameters, but not the active Q-switch. On the other hand, because the opening of the active Q-switch happens after the laser medium has been pumped to a certain or even saturated gain level, this time interval, i.e., the time of pulsing, will be much more regulated than the timing of the saturation onset of a free-running conventional passive Q-switch laser.

[0030] Thus, as a result, a laser with such hybrid Q-switch could produce sub-ns or even shorter pulses due to pulse characteristic of a passive laser and having the high reproducibility as those from an active laser. The pulse repetition rate will be controllable and can be adjusted to a value for the highest peak power or the maximum efficiency. Additionally, by adjusting the opening time window of the active Q-switch, the laser will work well above the lasing threshold without the occurrence of a sub-pulse so that pulses with much higher energy could be generated than a conventional passive laser. Compared to a laser with a normal active Q-switch, the laser of the present invention could generate pulses of shorter duration and higher peak power with same pumping energy, or generates same peak-power pulses with less pumping energy. Obviously, the hybrid Q-switch of the present invention combines the advantages of both active and passive Q-switches and eliminates their drawbacks.

[0031] In addition, the hybrid Q-switch is not mechanically more complicated than the corresponding active Q-switch. In fact, due to the addition of passive loss modulation, the depth of active loss modulation could be reduced so that a shorter EO/AO crystal or lower-voltage electronics can be used. Those electronics could be further simplified because of a relaxed requirement of short rise-time for the active switch due to the time delay of pulsing induced by the passive absorber. As a consequence, a laser device implementing the hybrid Q-switch of the invention could be more compact and less expensive than one implementing a corresponding active Q-switch, and further, could generate higher peak-power pulses at the same pumping condition (because of shorter pulse duration).

[0032] Nevertheless, compared to a passive one, a hybrid Q-switch based on an EO or AO active Q-switch may be still bulky and expensive. In another embodiment, a hybrid Q-switch according to the present invention is provided that comprises the combination of a fast rotating chopper and a saturable absorber. A rotating chopper is simple and the corresponding power consumption is negligible. The chopper could be very thin (<0.5mm) so that a laser with such a hybrid Q-switch will be as compact as one with only a saturable absorber. A motor that drives the chopper may easily achieve over 250 turns per second. Adding more opening holes/slits on the chopper can increase the repetition rate.

[0033] As mentioned early, a laser Q-switched by a rotating element only is not able to produce short-duration high-peak-power pulse due to slow evolution from edge cut to entire open. As the laser pulse is actually formed before entire open, the laser cavity suffers high loss.

[0034] However, by combining with a passive absorber, a time delay for forming a pulse is added, i.e., the

laser will not lase during the chopper early high-loss opening stage until the absorber is saturated. Therefore, a laser with this hybrid Q-switch suffers much less loss and can produce much shorter and higher-peak pulses than that with chopper-only Q-switch.

[0035] Fig. 4(a) shows a microchip laser embodied with a chopper/absorber hybrid Q-switch of the invention. 'Microchip laser' is a term means that the laser medium is thin (<couple mm) and is typically diode-pumped and the laser has a short cavity and so is extremely compact. For further compactness, the pump-side face of the laser medium 13 is coated for high reflection at the lasing wavelength and so it serves as one cavity mirror 11. Likewise, the output-side face of the absorber 16 at the further end is coated for high reflection at the lasing wavelength to serve as the other mirror 12 of the output side of the resonator cavity as shown in Fig. 4(a). In another embodiment, the absorber 16 is placed adjacent to the laser medium 13 and they may even be bonded together. In another embodiment, a single YAG crystal co-doped with Nd^{3+} and Cr^{4+} is used that acts as both laser-gain medium and saturable absorber. All the alternatives mentioned here are also applicable to the embodiment of the invention shown and described with respect to Fig. 3.

[0036] Referring back to Fig. 4(a), the chopper 17 is driven by a micromotor 18. The diameter of the chopper is under 12cm, and preferably, between 1.5~4.0 cm for a microchip laser device. There will be at least one opening hole or slit on the chopper to regulate pulse generation (active-Q-switch gate opening). As shown in Figure 4(b), an example of a chopper 17 with four opening slits 17a is depicted. The width of each slit should be larger than the resulting laser beam diameter, and preferably, about twice the width of the laser beam diameter. Preferably, the width of

each slit is narrow enough for avoiding sub-pulsing. In another embodiment, the width of the slits are adjustable. For example, two identical choppers with slits may be implemented with the crossover of two sets of slits adjusted to get a final required opening. They may thereafter be rotated together in fixed relation after being adjusted to have a proper crossover. Basically, the faster the evolution from edge cut to entire open, the better. Therefore, it is favorable to use a chopper of diameter as large as possible. In a high power laser that is usually of larger dimensions, a chopper with diameter larger than 12 cm might be implemented.

[0037] Lasers equipped with the hybrid Q-switch of the present invention find wide applications in fields requiring short pulses with high peak power. Some applications include, but are not limited to: LIBS, Laser induced fluorescence, Remote Sensing; Radar, Laser cleaning, Laser deposition, multi-photon absorption, and non-linear optics.

[0038] While there has been shown and described what is considered to be preferred embodiments of the invention, it will, of course, be understood that various modifications and changes in form or detail could readily be made without departing from the spirit of the invention. It is therefore intended that the invention be not limited to the exact forms described and illustrated, but should be constructed to cover all modifications that may fall within the scope of the appended claims.